

**From  $\Xi_b \rightarrow \Lambda_b \pi$  to  $\Xi_c \rightarrow \Lambda_c \pi$** 

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Using a successful framework for describing S-wave hadronic decays of light hyperons induced by a subprocess  $s \rightarrow u(\bar{u}d)$ , we presented recently a model-independent calculation of the amplitude and branching ratio for  $\Xi_b^- \rightarrow \Lambda_b \pi^-$  in agreement with a LHCb measurement. The same quark process contributes to  $\Xi_c^0 \rightarrow \Lambda_c \pi^-$ , while a second term from the subprocess  $cs \rightarrow cd$  has been related by Voloshin to differences among total decay rates of charmed baryons. We calculate this term and find it to have a magnitude approximately equal to the  $s \rightarrow u(\bar{u}d)$  term. We argue for a negligible relative phase between these two contributions, potentially due to final state interactions. However, we do not know whether they interfere destructively or constructively. For constructive interference one predicts  $\mathcal{B}(\Xi_c^0 \rightarrow \Lambda_c \pi^-) = (1.94 \pm 0.70) \times 10^{-3}$  and  $\mathcal{B}(\Xi_c^+ \rightarrow \Lambda_c \pi^0) = (3.86 \pm 1.35) \times 10^{-3}$ . For destructive interference, the respective branching fractions are expected to be less than about  $10^{-4}$  and  $2 \times 10^{-4}$ .

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## I INTRODUCTION

Most decays of charmed and beauty baryons observed up to now occur by  $c$  and  $b$  quark decays. In strange heavy flavor baryons an  $s$  quark may decay instead via the heavy flavor conserving subprocess  $s \rightarrow u(\bar{u}d)$  or  $su \rightarrow ud$ , with the  $c$  or  $b$  quark acting as a spectator. In strange charmed baryons an additional Cabibbo-suppressed subprocess  $cs \rightarrow cd$  can contribute. Early investigations of heavy flavor conserving two body hadronic decays of charmed and beauty baryons involving a low energy pion have been performed in Ref. [1–6]. In these studies a soft pion limit, partial conservation of the axial-vector current (PCAC) and current algebra have implied expressions for decay amplitudes in terms of matrix elements of four-fermion operators between initial and heavy baryon states. These matrix elements are difficult to estimate and depend strongly on models for heavy baryon wave functions.

Recently we proposed a model-independent approach for studying the decay  $\Xi_b^- \rightarrow \Lambda_b \pi^-$  [7] which had just been observed by the LHCb collaboration at CERN [8]. In the

heavy  $b$  quark limit this decay by  $s \rightarrow u(\bar{u}d)$  proceeds purely via an S-wave. Assuming that properties of the light diquark in  $\Xi_b^-$  are not greatly affected by the heavy nature of the spectator  $b$  quark, the decay amplitude for  $\Xi_b^- \rightarrow \Lambda_b \pi^-$  may be related to amplitudes for S-wave nonleptonic decays of  $\Lambda$ ,  $\Sigma$ , and  $\Xi$  which have been measured with high precision [9]. We calculated a branching fraction for  $\Xi_b^- \rightarrow \Lambda_b \pi^-$  consistent with the range allowed in the LHCb analysis. Our purpose now is to extend this calculation to charmed baryon decays  $\Xi_c^0 \rightarrow \Lambda_c \pi^-$  and  $\Xi_c^+ \rightarrow \Lambda_c \pi^0$ .

Sec. II summarizes the result of Ref. [7] for the amplitude of  $\Xi_b^- \rightarrow \Lambda_b \pi^-$ , in which the underlying quark transition is  $s \rightarrow u(\bar{u}d)$ . This result is then applied to a contribution of the same quark subprocess to  $\Xi_c^0 \rightarrow \Lambda_c \pi^-$ . A second term in this amplitude due to the subprocess  $cs \rightarrow cd$  is studied in Sec. III. The total amplitude and the branching ratios for  $\Xi_c^0 \rightarrow \Lambda_c \pi^-$  and  $\Xi_c^+ \rightarrow \Lambda_c \pi^0$  are calculated in Sec. IV while Section V concludes.

## II $s \rightarrow u(\bar{u}d)$ TERM IN $\Xi_b^- \rightarrow \Lambda_b \pi^-$ AND $\Xi_c^0 \rightarrow \Lambda_c \pi^-$

We will use notations which are common for describing hadronic hyperon decays [9]. The effective Lagrangian for  $B_1 \rightarrow B_2 \pi$  given by

$$\mathcal{L}_{\text{eff}} = G_F m_\pi^2 [\bar{\psi}_2 (A + B \gamma_5) \psi_1] \phi_\pi \quad (1)$$

involves two dimensionless parameters  $A$  and  $B$  describing S-wave and P-wave amplitudes, respectively. Here  $G_F = 1.16638 \times 10^{-5} \text{ GeV}^{-2}$  is the Fermi decay constant. The partial width is

$$\Gamma(B_1 \rightarrow B_2 \pi) = \frac{(G_F m_\pi^2)^2}{8\pi m_1^2} q [(m_1 + m_2)^2 - m_\pi^2] |A|^2 + [(m_1 - m_2)^2 - m_\pi^2] |B|^2, \quad (2)$$

where  $q$  is the magnitude of the final three-momentum of either particle in the  $B_1$  rest frame.

Consider first  $\Xi_b^- \rightarrow \Lambda_b \pi^-$  studied in Ref. [7]. In the heavy  $b$  quark limit the light quarks  $s$  and  $d$  in  $\Xi_b^- = bsd$  are in an S-wave state antisymmetric in flavor with total spin  $S = 0$ . The light quarks  $u$  and  $d$  in the  $\Lambda_b = bud$  are also in an S-wave state with  $I = S = 0$ . In the decay  $\Xi_b^- \rightarrow \Lambda_b \pi^-$  which proceeds via  $s \rightarrow u(\bar{u}d)$  the  $b$  quark acts as a spectator. The transition among light quarks is thus one with  $J^P = 0^+ \rightarrow 0^+ \pi$ , and hence is purely a parity-violating S wave. Thus it may be related to parity-violating S-wave amplitudes in nonleptonic decays of the hyperons  $\Lambda$ ,  $\Sigma$ , and  $\Xi$ .

S-wave hadronic decays of hyperons,  $B_1 \rightarrow B_2 \pi$ , where the baryons  $B_1$  and  $B_2$  belong to the lowest SU(3) octet baryons, have been known for fifty years to be described well by using PCAC and current algebra and assuming octet dominance [10, 11]. An equivalent and somewhat more compact parametrization of these amplitudes based on duality has been suggested a few years later [12]. All hyperon S-wave amplitudes may be expressed in terms of an overall normalization parameter  $x_0$  and a parameter  $F$  describing the ratio of antisymmetric and symmetric three-octet coupling. (In the soft pion limit the commutator of the axial charge with the weak Hamiltonian represents a third octet in addition to the two baryons.) Thus one finds [7, 12]

$$A(\Lambda \rightarrow p \pi^-) = -(2F + 1)x_0/\sqrt{6},$$

Table I: Predicted and observed S-wave amplitudes  $A$  for nonleptonic hyperon decays. Predicted values are for best-fit parameters  $F = 1.652$ ,  $x_0 = 0.861$ .

Decay	Predicted $A$ amplitude	Observed value [9]	Predicted value
$\Lambda \rightarrow p\pi^-$	$-(2F+1)x_0/\sqrt{6}$	$-1.47 \pm 0.01$	-1.51
$\Lambda \rightarrow n\pi^0$	$(2F+1)x_0/(2\sqrt{3})$	$1.07 \pm 0.01$	1.07
$\Sigma^+ \rightarrow n\pi^+$	0	$0.06 \pm 0.01$	0
$\Sigma^+ \rightarrow p\pi^0$	$-(2F-1)x_0/\sqrt{2}$	$-1.48 \pm 0.05$	-1.40
$\Sigma^- \rightarrow n\pi^-$	$-(2F-1)x_0$	$-1.93 \pm 0.01$	-1.98
$\Xi^0 \rightarrow \Lambda\pi^0$	$(4F-1)x_0/(2\sqrt{3})$	$1.55 \pm 0.03$	1.39
$\Xi^- \rightarrow \Lambda\pi^-$	$(4F-1)x_0/\sqrt{6}$	$2.04 \pm 0.01$	1.97

$$\begin{aligned}
A(\Sigma^+ \rightarrow n\pi^+) &= 0, \\
A(\Sigma^- \rightarrow n\pi^-) &= -(2F-1)x_0, \\
A(\Xi^- \rightarrow \Lambda\pi^-) &= (4F-1)x_0/\sqrt{6},
\end{aligned} \tag{3}$$

while amplitudes involving a neutral pion are related to these amplitudes by isospin. Using best fit values  $F = 1.652$ ,  $x_0 = 0.861$ , one finds good agreement between predicted and measured amplitudes as shown in Table I (see [7]). The relative signs of S-wave amplitudes are convention-dependent and differ from those in Ref. [9]. An overall sign change is also permitted, associated with two possible signs of  $x_0$ .

In the decay  $\Xi_b^- \rightarrow \Lambda_b\pi^-$ , which also proceeds by  $s \rightarrow u(\bar{u}d)$ , the light diquarks  $sd$  and  $ud$  in the initial and final baryons form each a spinless antisymmetric  $3^*$  of flavor SU(3). The weak transition occurs between this pair of diquarks while the  $b$  quark acts as a spectator. Neglecting the effect of the heavy  $b$  quark on relevant properties of the light diquarks, this amplitude is expected to be equal to an amplitude for a transition between light hyperons,  $\Lambda \rightarrow \Lambda(\bar{u}u)$ , in which the diquarks in initial and final hyperons are also in an antisymmetric  $3^*$  while the  $s$  quark acts as a spectator. Thus one finds [7]

$$A(\Xi_b^- \rightarrow \Lambda_b\pi^-) = (5F-2)x_0/3. \tag{4}$$

Using the best fit values of  $x_0$  and  $F$  one obtains  $A(\Xi_b^- \rightarrow \pi^-\Lambda_b) = \pm 1.796$ .

One may improve this calculation somewhat by including SU(3) breaking. We note that the measured S-wave amplitudes for  $\Lambda \rightarrow p\pi^-$  and  $\Sigma^- \rightarrow n\pi^-$  alone determine a slightly different value for  $x_0$ ,  $x_0 = 0.835$  having practically no effect on  $F$ . The relation

$$A(\Xi_b^- \rightarrow \Lambda_b\pi^-) = -\frac{1}{2\sqrt{6}}A(\Lambda \rightarrow p\pi^-) - \frac{3}{4}A(\Sigma^- \rightarrow n\pi^-), \tag{5}$$

and experimental values of the amplitudes on the right-hand side imply

$$A(\Xi_b^- \rightarrow \Lambda_b\pi^-) = \pm 1.75 \pm 0.26. \tag{6}$$

In the three amplitudes occurring in (5) an  $s$  quark occurs in the decaying baryons taking part in the transition but not as a spectator. This leads to a common redefinition of  $x_0$  which now includes SU(3) breaking. While the value (6) includes this effect of SU(3) breaking we have attributed to it an uncertainty of 15% caused by assuming octet dominance and by neglecting the effect of the heavy  $b$  quark on properties of the light diquarks.

The considerations and calculation leading to (6) apply also to the contribution of the transition  $s \rightarrow u(\bar{u}d)$  to the S-wave amplitude for  $\Xi_c^0 \rightarrow \Lambda_c \pi^-$ . Here one replaces a spectator  $b$  quark in  $\Xi_b^-$  and  $\Lambda_b$  by a  $c$  quark in  $\Xi_c^0 = csd$  and  $\Lambda_c = cud$ , assuming that the  $c$  quark mass is much heavier than the light  $u, d$  and  $s$  quarks. In this approximation we have

$$A_{s \rightarrow u\bar{u}d}(\Xi_c^0 \rightarrow \Lambda_c \pi^-) = A(\Xi_b^- \rightarrow \Lambda_b \pi^-) . \quad (7)$$

### III $cs \rightarrow cd$ CONTRIBUTION TO $\Xi_c^0 \rightarrow \Lambda_c \pi^-$

The S-wave amplitude for  $\Xi_c^0 \rightarrow \Lambda_c \pi^-$  obtains a second contribution from an “annihilation” subprocess  $cs \rightarrow cd$  involving an interaction between the  $c$  and  $s$  quarks in the  $\Xi_c^0$ . We will now present in some detail a method proposed by Voloshin [3, 13, 14] for calculating this amplitude in the heavy  $c$ -quark limit in terms of differences among measured total widths of charmed baryons.

The effective weak Hamiltonian responsible for this Cabibbo-suppressed strangeness-changing transition is given by

$$H_W = -\sqrt{2}G_F \cos \theta_C \sin \theta_C \left[ (C_+ + C_-)(\bar{c}_L \gamma_\mu s_L)(\bar{d}_L \gamma_\mu c_L) + (C_+ - C_-)(\bar{d}_L \gamma_\mu s_L)(\bar{c}_L \gamma_\mu c_L) \right] . \quad (8)$$

In the following we will use values  $C_+ = 0.80$  and  $C_- = 1.55$  for Wilson coefficients calculated in a leading-log approximation at a scale  $\mu = m_c = 1.4$  GeV corresponding to  $\alpha_s(m_c)/\alpha(m_W) = 2.5$ . Applying a soft pion limit and using PCAC, the amplitude due to  $cs \rightarrow cd$  is given in our normalization (1) [which is related to that of Ref. [3] by a factor  $\xi/(G_F m_\pi^2)$ ] by

$$\begin{aligned} A_{cs \rightarrow cd}(\Xi_c^0 \rightarrow \Lambda_c \pi^-) &= \\ \frac{\sqrt{2}\xi}{f_\pi m_\pi^2} \cos \theta_C \sin \theta_C &\langle \Lambda_c | (C_+ + C_-)(\bar{c}_L \gamma_\mu s_L)(\bar{u}_L \gamma_\mu c_L) + (C_+ - C_-)(\bar{u}_L \gamma_\mu s_L)(\bar{c}_L \gamma_\mu c_L) | \Xi_c^0 \rangle \\ &= \frac{\xi}{2\sqrt{2}f_\pi m_\pi^2} \cos \theta_C \sin \theta_C [0.75x - 2.35y] . \end{aligned} \quad (9)$$

Here  $f_\pi = 0.130$  GeV,  $\xi \equiv 2m_{\Xi_c^0}/\sqrt{(m_{\Xi_c^0} + m_{\Lambda_c})^2 - m_{\pi^-}^2} = 1.04$  [15].

In the above one defines two matrix element  $x$  and  $y$  (of dimension  $\text{GeV}^3$ ) in which the contribution of the axial-current vanishes for a heavy  $c$  quark,

$$\begin{aligned} x &\equiv -\langle \Lambda_c | (\bar{c} \gamma_\mu c)(\bar{u} \gamma_\mu s) | \Xi_c^0 \rangle , \\ y &\equiv -\langle \Lambda_c | (\bar{c}_i \gamma_\mu c_k)(\bar{u}_k \gamma_\mu s_i) | \Xi_c^0 \rangle , \end{aligned} \quad (10)$$

where  $i, k$  are color indices. Using flavor SU(3) one may write these two terms as differences of diagonal matrix elements of four fermion operators,  $\langle \mathcal{O} \rangle_{\psi-\phi} \equiv \langle \psi | \mathcal{O} | \psi \rangle - \langle \phi | \mathcal{O} | \phi \rangle$ , for charmed baryon states belonging to V-spin and U-spin doublets:

$$\begin{aligned} x &= \frac{1}{2} \langle (\bar{c} \gamma_\mu c) [(\bar{u} \gamma_\mu u) - (\bar{s} \gamma_\mu s)] \rangle_{\Xi_c^0 - \Lambda_c} = \frac{1}{2} \langle (\bar{c} \gamma_\mu c) [(\bar{s} \gamma_\mu s) - (\bar{d} \gamma_\mu d)] \rangle_{\Lambda_c - \Xi_c^+} , \\ y &= \frac{1}{2} \langle (\bar{c} \gamma_\mu c) [(\bar{u} \gamma_\mu u) - (\bar{s} \gamma_\mu s)] \rangle_{\Xi_c^0 - \Lambda_c} = \frac{1}{2} \langle (\bar{c} \gamma_\mu c) [(\bar{s} \gamma_\mu s) - (\bar{d} \gamma_\mu d)] \rangle_{\Lambda_c - \Xi_c^+} . \end{aligned} \quad (11)$$

Within a heavy quark expansion the quantities  $x$  and  $y$  can be used to describe differences of inclusive decay rates among the above three charmed baryons. Adding contributions of hadronic and semileptonic Cabibbo-favored and singly Cabibbo-suppressed decays one finds in the flavor SU(3) limit [3, 13, 14]:

$$\begin{aligned} \Gamma(\Xi_c^0) - \Gamma(\Lambda_c) &= \frac{G_F^2 m_c^2}{4\pi} \left( -x [\cos^4 \theta_C C_+ C_- + \frac{1}{4} \cos^2 \theta \sin^2 \theta (6C_+ C_- + 5C_+^2 + 5C_-^2)] \right. \\ &\quad \left. + y [3 \cos^4 \theta_C C_+ C_- + \frac{3}{4} \cos^2 \theta_C \sin^2 \theta_C (6C_+ C_- - 3C_+^2 + C_-^2) + 2] \right) , \\ \Gamma(\Lambda_c) - \Gamma(\Xi_c^+) &= \frac{G_F^2 m_c^2}{4\pi} \left( -x \frac{1}{4} \cos^4 \theta_C (5C_+^2 + 5C_-^2 - 2C_+ C_-) \right. \\ &\quad \left. + y [\frac{3}{4} \cos^4 \theta_C (C_-^2 - 3C_+^2 - 2C_+ C_-) - 2(\cos^2 \theta_C - \sin^2 \theta_C)] \right) . \end{aligned} \quad (12)$$

Substituting the above values of  $C_+, C_-$  and  $\cos \theta_C = 0.97424, \sin \theta_C = 0.2253$  [15] one has

$$\begin{aligned} \Gamma(\Xi_c^0) - \Gamma(\Lambda_c) &= \frac{G_F^2 m_c^2}{4\pi} [-1.39 x + 5.64 y] , \\ \Gamma(\Lambda_c) - \Gamma(\Xi_c^+) &= \frac{G_F^2 m_c^2}{4\pi} [-2.87 x - 3.15 y] . \end{aligned} \quad (13)$$

Eliminating  $x$  and  $y$  in these equations Eq. (9) now implies

$$A_{cs \rightarrow cd}(\Xi_c^0 \rightarrow \Lambda_c \pi^-) = -\frac{\sqrt{2} \pi \xi \cos \theta_C \sin \theta_C}{G_F^2 m_c^2 m_\pi^2 f_\pi} \left( 0.44 [\Gamma(\Xi_c^0) - \Gamma(\Lambda_c)] + 0.05 [\Gamma(\Lambda_c) - \Gamma(\Xi_c^+)] \right) . \quad (14)$$

Using the measured charmed baryon lifetimes [15]

$$\tau(\Xi_c^0) = 0.112_{-0.010}^{+0.013} \text{ ps} , \quad \tau(\Xi_c^+) = 0.442 \pm 0.026 \text{ ps} , \quad \tau(\Lambda_c) = 0.200 \pm 0.006 \text{ ps} , \quad (15)$$

we calculate

$$A_{cs \rightarrow cd}(\Xi_c^0 \rightarrow \Lambda_c \pi^-) = -(1.85 \pm 0.40 \pm 0.40) \left( \frac{1.4 \text{ GeV}}{m_c} \right)^2 . \quad (16)$$

The first (symmetrized) error corresponds to errors in lifetime measurements, while the second one is associated with uncertainties due to SU(3) breaking and due to a finite  $c$ -quark mass. We checked that replacing the Wilson coefficients  $C_\pm$  by values calculated beyond the leading-log approximation,  $C_+ = 0.80, C_- = 1.63$  [16], has a negligible effect on the central value.

## IV DECAY RATES OF $\Xi_c^0 \rightarrow \Lambda_c \pi^-$ AND $\Xi_c^+ \rightarrow \Lambda_c \pi^0$

Combining Eqs. (6), (7) and (16) and adding errors in quadrature we find for  $m_c = 1.4$  GeV and destructive interference

$$A(\Xi_c^0 \rightarrow \Lambda_c \pi^-) = |A_{s \rightarrow u\bar{u}d}(\Xi_c^0 \rightarrow \Lambda_c \pi^-)| + A_{cs \rightarrow cd}(\Xi_c^0 \rightarrow \Lambda_c \pi^-) = -0.10 \pm 0.62, \quad (17)$$

while for constructive interference we find

$$A(\Xi_c^0 \rightarrow \Lambda_c \pi^-) = -|A_{s \rightarrow u\bar{u}d}(\Xi_c^0 \rightarrow \Lambda_c \pi^-)| + A_{cs \rightarrow cd}(\Xi_c^0 \rightarrow \Lambda_c \pi^-) = -3.60 \pm 0.62. \quad (18)$$

In the former case the small central value of the amplitude is the result of cancellation between two real contributions of approximately equal magnitudes but opposite signs.

In principle each of the two terms in the above two equations could involve a phase due to final state strong interactions. A final state interaction one might anticipate in S-wave  $\Xi_c \rightarrow \Lambda_c \pi$  or  $\Xi_b \rightarrow \Lambda_b \pi$  would be the effect of  $\Sigma_c^*$  or  $\Sigma_b^*$ . However, their parity is wrong for such contributions. Final state interactions are negligible in these heavy baryon decays for the same reason they are small in S-wave nonleptonic hyperon decays. This is demonstrated by the well-fitted real amplitudes in Table I and by a triangle relation which follows from more general considerations [17, 18],

$$2A(\Xi^- \rightarrow \pi^- \Lambda) + A(\Lambda \rightarrow \pi^- p) = -(3/2)^{1/2} A(\Sigma^- \rightarrow \pi^- n), \quad (19)$$

which holds best for real values. The second term in  $\Xi_c^0 \rightarrow \Lambda_c \pi^-$  due to  $cs \rightarrow cd$  is real and negative, given in (14) in terms of width differences among charmed baryons.

For constructive interference, the branching fraction is predicted by Eq. (2) to be  $\mathcal{B}(\Xi_c^0 \rightarrow \Lambda_c \pi^-) = (1.94 \pm 0.70) \times 10^{-3}$ . This branching ratio is somewhat smaller than that of the corresponding  $\Xi_b^-$  decay,  $\mathcal{B}(\Xi_b^- \rightarrow \Lambda_b \pi^-) = (6.00 \pm 1.81) \times 10^{-3}$ , calculated using (6) and the  $\Xi_b^-$  lifetime which is roughly an order of magnitude larger than  $\tau(\Xi_c^0)$  [15]. For destructive interference, at 90% c.l. it is less than  $\sim 10^{-4}$ . The amplitude for  $\Xi_c^+ \rightarrow \Lambda_c \pi^0$  is related to that for  $\Xi_c^0 \rightarrow \Lambda_c \pi^-$  by the  $\Delta I = 1/2$  rule, which holds for both contributions. Consequently, the partial decay rate is half that for  $\Xi_c^0 \rightarrow \Lambda_c \pi^-$ . Because of the larger lifetime of the  $\Xi_c^+$ , which is about four times that of  $\Xi_c^0$ , the corresponding branching fraction is predicted to be about two times larger,  $(3.86 \pm 1.35) \times 10^{-3}$  for constructive interference or less than about  $2 \times 10^{-4}$  for destructive interference.

## V CONCLUSIONS

We have discussed the heavy-flavor-conserving decays  $\Xi_c^0 \rightarrow \Lambda_c \pi^-$  and  $\Xi_c^+ \rightarrow \Lambda_c \pi^0$  within the context of current algebra, taking separate account of amplitudes governed by the subprocesses  $s \rightarrow u\bar{u}d$  and  $cs \rightarrow cd$ . We have used a previous result for  $\Xi_b^- \rightarrow \Lambda_b \pi^-$  to obtain the former amplitude, while updating an estimate by Voloshin for the latter. The relative signs of the amplitudes are not determined. For constructive interference, we predict  $\mathcal{B}(\Xi_c^0 \rightarrow \Lambda_c \pi^-) = (1.94 \pm 0.70) \times 10^{-3}$  with half the rate and twice the branching fraction for  $\Xi_c^+ \rightarrow \Lambda_c \pi^0$ . For destructive interference, the former branching fraction is expected to be less than about  $10^{-4}$  or twice that for the latter.

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